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Design Parameter Characteristics in a Subsea Rigid Jumper

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Abstract

Functionally, subsea jumpers in a short pipe connector are used to transport production fluids between two subsea components such as a tree and manifold, manifold and manifold or manifold and export sled. In the design of a rigid jumper system, all parts of the system should be analyzed with respect to reliability, safety, costs and expected failure rates and to minimize failures and maintenance for the life of the design. Rigid jumpers are standard-shaped pipes that can withstand high static and dynamic loads generated by internal pressure, temperature and external fluid effects. This paper describes a fluid structure interaction modeling technique that incorporates all of the significant behavioral effects that influence the thermal and geometric characteristics of jumpers for operating, hydraulic and service fluids. The use of nonlinear finite element code allowed the creation of a jumper model of a coupled fluid structure interaction problem. The results and recommendations presented in this paper will provide assistance to the industry in the design and analysis of subsea jumpers.

Keywords: Subsea environment; Jumper; Extreme environmental condition; Fluid structure interaction

Introduction

Subsea fields have been developed using a variety of tie-in systems over the past decades. Subsea jumpers are widely used today in various ways in subsea oil/gas production systems. Functionally, a subsea jumper is a short pipe connector used to transport production fluid between two subsea components such as a tree and manifold, manifold and manifold or manifold and export sled (Figure 1a). Different types of horizontal and vertical tie-in systems and associated connection tools are used for the tie-in of flow lines, umbilicals and other applications in service [1].

In the design of a rigid jumper system, all parts of the system should be analyzed with respect to reliability, safety, costs and expected failure rates and to minimize failures and maintenance for the life of the design. In addition, the systems are periodically de pressurized during operation for maintenance. Due to the complicated and wide variety of load conditions handled, subsea rigid jumpers must go through several analysis iterations to reach an optimal design. Rigid jumpers have to possess enough flexibility to accommodate end thermal expansion and installation misalignments, which are governing loads for jumper strength analysis in the majority of cases. The jumper connector capacity envelope can also be the driving factor for increasing flexibility. To achieve these requirements, the typical span length of a rigid jumper is from 20 to 50 m. It is usually fabricated into an M-shape (Figure 1b), L-shape or inverted U-shape by adding vertical legs and using steel bends, tees and elbows. This is basically a fluid structure interaction (FSI) problem, in which internal or external flow interacts with the structure to create stresses and pressures that deform the pipe and consequently alter the flow of the fluid [2]. Thus, the interaction phenomenon is very important in the design of the jumper. This paper presents the results of an investigation of the collapse strength of pipes of varying shapes, in which ovality, temperature and internal velocity are considered.

Standard Code for Pipeline

Among the current industry practice regulations, the standard mechanical design for ultra-deep-water pipelines is based on API RP 1111 [3], which have been used for deep-water projects in West Africa. DNV OS F101 [4] has mostly been used for deep-water projects in offshore Brazil and Europe. DNV OS F101 includes no limitations on water depth. However, when this standard is applied in deep water, for which experience is limited, special considerations must be made. The original collapse pressures listed in DNV OS F101 are only applicable to pipelines that are straight in a stress-free condition and are not applicable to bends, for example [5]. The characteristic collapse pressure ( ) is calculated from equations (1)-(3):

$$(P_c - P_{el})(P_c^2 - P_p^2) = P_c P_{el} P_p f_o \frac{D}{t} \tag{1}$$

$$P_{el} = 2E\left(\frac{t}{D}\right)^3 / (1-\nu^2), P_p = f_y \alpha_{fab} \frac{2t}{D}, f_o = \frac{D_{\max} - D_{\min}}{D} \tag{2}$$

where P_c is the characteristic collapse pressure, P_{el} is the elastic collapse pressure, P_p is the plastic collapse pressure, f_y is the yield stress to be used in the design, E is the elastic modulus, α_{fab} is the fabrication factor, t is the wall thickness of the pipe and ν is the Poisson ratio. The external pressure at any point along the pipeline shall meet the following criterion:

$$P_e - P_{\min} \leq \frac{P_c}{\gamma_m \gamma_{SC}} \tag{3}$$

where P_e is the external pressure, γ_m is the material resistance factor and γ_{SC} is the safety class resistance factor.

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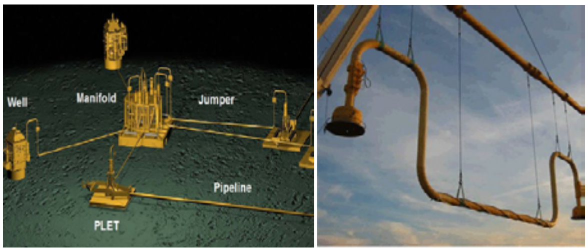

(a) Subsea oil/gas production system (b) Typical M-shaped jumper

Figure 1: Subsea oil/gas production system and M-shaped jumper.

In this study, the collapse pressure is evaluated using empirical models and numerical analysis. It is well known that these design codes contain simplifications and assumptions that result in a less accurate assessment. Therefore, an advanced method of assessment, such as the finite element method, is necessary to overcome these kinds of problems. Thus, the assessment of the prediction of collapse pressure by means of numerical analysis is performed using nonlinear finite element analysis (FEA) software.

Analysis Procedure

This section summarizes the sensitivity analysis procedure used for the subsea rigid jumper under extreme conditions, as shown in Figure 1.

The governing equations of incompressible thermal flow in a steady-state single phase are the conservation of mass, momentum and energy. In this study, the turbulence model and the wall function are applied in the steady-state thermal flow analysis. Full coupling is needed between the particles and the continuous phase to predict the effect of the particles on the continuous-phase flow field. We use 200 particles to calculate the effect of the particles on the continuous fluid. The density and viscosity of fluid in the subsea jumper are considered in the computational fluid dynamics (CFD) simulation.

Nonlinear large deflection and bilinear isotropic hardening models are adopted to numerically simulate a nonlinear FEA. The following ANSYS [6] non-linear FEA is used in this study for the computations of collapse strength of subsea jumper structures. The ANSYS nonlinear FEA is the most refined method of those currently available and is believed to provide the most accurate solutions. It is important to realize that the modelling technique applied must be capable of representing the actual structural behaviour associated with geometrical nonlinearity, material nonlinearity (temperature), type and magnitude of initial imperfections (ovality) due to installation and transportation, boundary conditions, loading conditions and mesh size, etc.

Scenario selection for design parameters

To determine sensitivity and the effect of design parameters on the collapse strength of varying pipe shapes, ovality, temperature and internal fluid velocity are considered. Latin hypercube sampling (LHS) is a very effective and popular procedure for the propagation of epistemic uncertainty in analyses of complex systems. A relatively small Latin hypercube sample can be used to cover a very large number of samples, making LHS both effective and popular. Analyses of complex systems typically involve large and computationally demanding models. As a consequence, it is necessary to use an efficient sampling procedure such as LHS in the propagation of epistemic uncertainty because the number of model evaluations that can be performed is limited by computational cost. Three design parameters are considered, temperature, velocity and ovality. The range of each variable is divided into m intervals, so one sample will be taken from every interval. The input is taken from a random selection of scenarios that covers the whole range of variables, such that the sampling scheme does not require additional samples for more dimensions (variables), which is one of the main advantages of LHS. More detailed information on the basis and application of the LHS technique can be found in Ye (1998) [7].

Numerical Analysis

M-shaped rigid jumper

Rigid jumpers are standard-shaped pipes that can withstand the high static and dynamic loads generated by internal pressure, temperature and external fluid effects. A jumper usually connects a tree with a manifold. A rigid M-shaped jumper is the configuration that is studied here, and its dimensions are shown in Figures 2 and 3. The rigid jumper is made of grade X65 carbon steel. The main dimensions and general information on the target jumper are summarized in Table 1.

Parametric scenario selection

Three random variables must be considered, temperature (X1), velocity (X2) and ovality (X3). These parameters are considered to be independent and important parameters related to collapse pressure. Ovality and temperature are considered, according to DNV criteria, as 0%-3% and 50-200°C, respectively. The general subsea pipeline velocity is considered to be 1-5 m/s. We thus consider three random parameters, ovality, temperature and velocity. The temperature and velocity of fluid are quite distinct based on characteristics of oil and gas. Therefore, a certain range of temperature and velocity are assumed according to the probability density function shown in Figure 4. The initial imperfection of a pipeline (ovality) is considered with DNV OS F101 code as the probability density function.

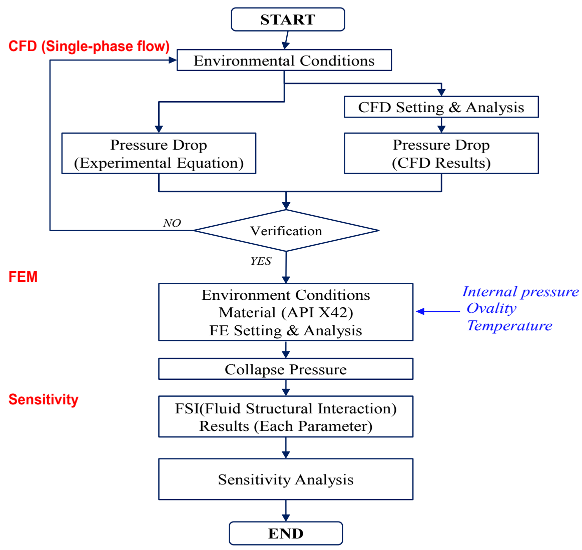

Figure 2: Procedure for fluid-structure interaction analysis.

Properties of a rigid M-shaped jumper	
Density, kg/m³	7861.092
Outer diameter, mm	273.050
Wall thickness, mm	31.750

Table 1: General information on the target pipeline.

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Fifty scenarios are randomly selected by the sampling method. The probability density distribution of each random variable is divided into 50 segments, with the interval of each segment determined such that the area below the curve between the probability density versus random variable must be equal, as shown in Figure 2. The representative value of a random variable for a segment is taken as the average value of that segment. The center of the area is taken as the representative value of the segment at the tail of the probability density distribution. Table 2 lists 50 representative values for each random variable.

Sensitivity Investigation

FSI analysis

To simulate the fluid and structural behaviour of the target structure with and without lateral pressure, attention must be paid to several considerations. In this study, the turbulence model and the wall function are applied in the steady-state thermal flow analysis. Full coupling is needed between the particles and the continuous phase to predict the effect of the particles on the continuous-phase flow field.

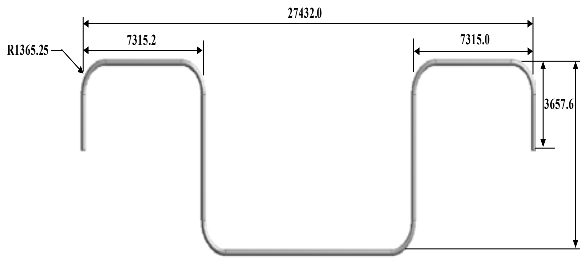

Figure 3: Dimensions of the M-shaped rigid jumper.

Scenario	Temperature (°C)	Ovality (%)	Velocity (m/s)	Scenario	Temperature (°C)	Ovality (%)	Velocity (m/s)
1	159.56	2.79	4.16	26	183.57	0.63	4.48
2	198.54	2.49	1.92	27	72.51	2.85	3.36
3	54.50	0.27	2.88	28	138.55	1.17	4.32
4	174.56	1.35	4.64	29	150.55	2.97	2.48
5	66.51	0.69	2.96	30	192.57	2.07	1.68
6	102.53	1.47	3.92	31	132.54	2.13	1.20
7	63.51	2.61	2.08	32	81.52	2.55	4.24
8	99.53	0.45	4.80	33	51.50	2.43	3.68
9	186.57	0.99	3.60	34	168.56	1.65	3.04
10	123.54	2.19	1.76	35	126.54	1.83	1.52
11	108.53	1.05	4.72	36	57.50	0.03	2.40
12	156.55	0.57	3.44	37	153.55	0.93	1.36
13	111.53	1.11	4.40	38	144.55	0.39	1.04
14	96.52	2.31	2.00	39	180.57	1.95	3.20
15	75.51	1.77	1.12	40	87.52	0.87	3.76
16	78.52	0.21	4.56	41	141.55	1.23	1.28
17	69.51	1.59	3.52	42	135.54	0.81	2.24
18	165.56	2.91	1.60	43	171.56	2.67	2.32
19	195.57	1.89	2.56	44	60.51	1.53	3.84
20	84.52	1.41	1.44	45	129.54	1.29	4.88
21	105.53	0.15	1.84	46	177.56	2.37	2.64
22	117.53	2.01	2.16	47	147.55	0.09	3.28
23	189.57	0.75	2.72	48	93.52	0.33	4.96
24	114.53	2.25	4.08	49	90.52	0.51	4.00
25	120.54	1.71	2.80	50	162.56	2.73	3.12

Table 2: Scenario selection.

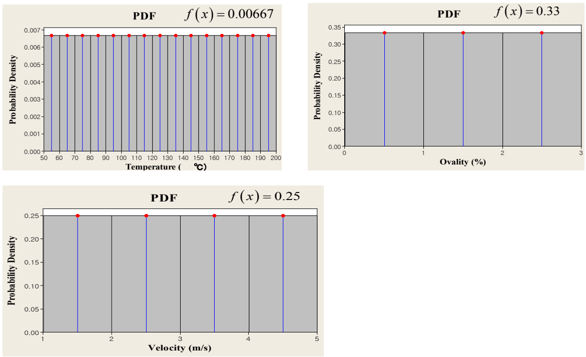

Figure 4: Probability density functions (PDF) for temperature, ovality and velocity.

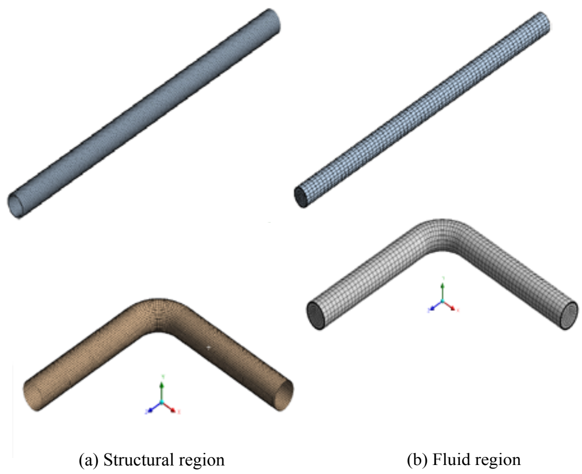

Figure 5: Numerical modelling for FSI analysis.

This effect is calculated using 200 particles, with density and fluid viscosity in the subsea jumper considered for CFD simulation.

The simulation must be capable of modeling the structural behaviour in both the linear and non-linear regions, including large displacements, elasto-plastic deformations and associated plasticity effects. The shell elements in the ANSYS element library generally satisfy these criteria and can thus be used to model the steel plate elements of plate-stiffened panels. There are different types of shell elements available in this library. Shell 181 three-dimensional thin isoparametric quadrilateral elements with four nodes and six degrees of freedom per node are used to model the steel plate elements in this study, as they are considered the most suitable for the proposed FEA.

The following ANSYS Workbench 14.0 CFD and nonlinear FEA is used in this study to compute the collapse strength of the subsea jumpers. Figure 5 shows the numerical modeling for the structural and fluid regions used in the ANSYS Workbench.

For the CFD study, we use crude oil, which is the most likely product to be transported in a subsea field. Details of the properties of this oil are listed in Tables 3 and 4. The ANSYS metal plasticity model is used in all of the structural analyses reported here. This model implements the von Mises yield surface to define isotropic yielding, associated plastic flow theory and either perfect plasticity or isotropic

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hardening behaviour. The finite element models incorporate pipeline yield stresses of 450 MPa. The elastic modulus and the Poisson ratio are 300 GPA and 0.3, respectively.

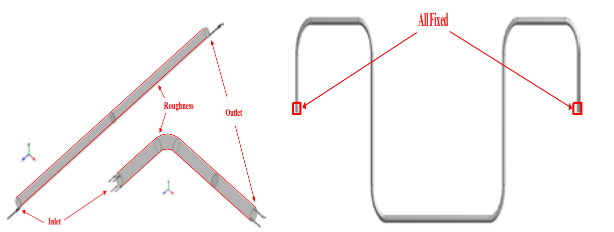
The boundary conditions are represented in Figure 6 for the CFD and FE analyses. To reduce the boundary effect on the flow analysis, dummy regions are defined at both ends of the piping models and their length is 10 times the pipe diameter. The CFD modeling of the pipe should be allocated using a very fine mesh, based on the results of a mesh convergence test. The structural analysis considers the effect of de-rating values for the yield stress of C-Mn and duplex stainless steels, as shown in Figure 7.

Analysis Results and Discussion

Table 4 summarizes the collapse pressure computations obtained with the FE models and DNV code calculations. Figure 8 shows the results of the analysis of the three variables in terms of collapse pressure vs. temperature, ovality and velocity, based on the computations of the present study and the DNV code. The DNV code, which was developed

General information	
Type	Medium crude oil
Location	Hungo, Angola
Density, kg/m³	880
Kinematic viscosities	7.18 (62.5°C) 5.77 (75.0°C) 2.93 (100°C)

Table 3: Properties of crude oil.



(a) (b)

Figure 6: Boundary conditions of a rigid jumper: (a) fluid region and (b) structural region.

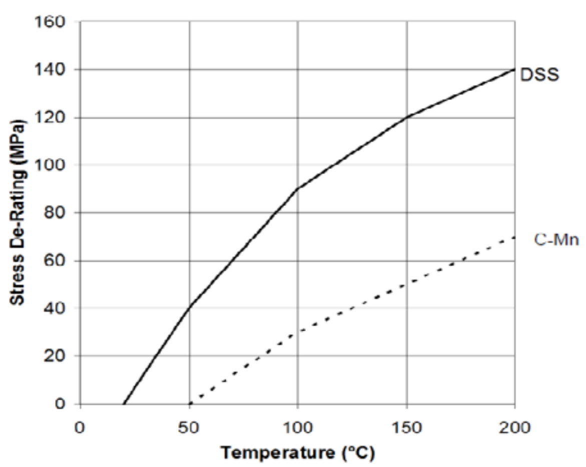
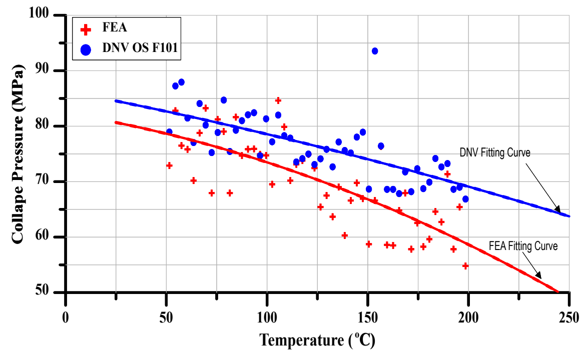
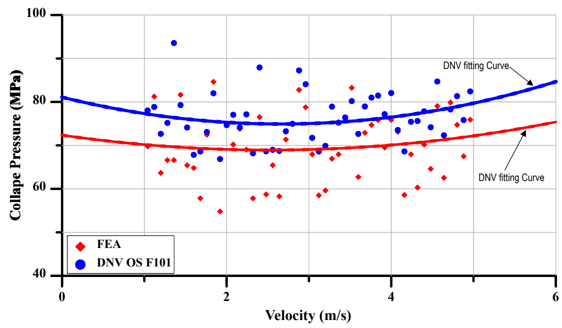


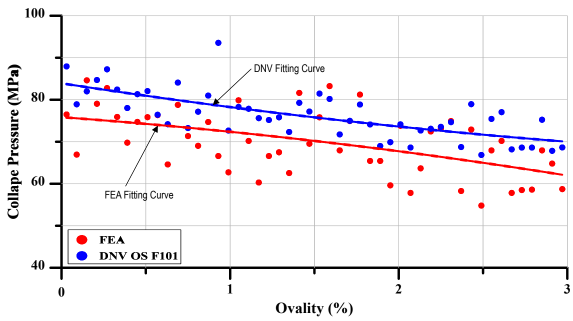
Figure 7: De-rating values for yield stress of C-Mn and duplex stainless steels [5].



(a) Temperature vs. collapse pressure



(b) Velocity vs. collapse pressure



(a) Ovality vs. collapse pressure

Figure 8: Comparison between the collapse pressure in the present study and DNV code.

based on the principal dimensions and characteristic of pipeline, tends to overestimate the values compared with the computations in the current study.

Figure 9 shows the results of the sensitivity analysis provided by the ANSYS nonlinear FEA for the collapse pressure of the subsea jumper under various operational conditions of temperature, ovality and fluid velocity. It is clear that, as expected, temperature significantly reduces the collapse pressure of the jumper compared with the variables of velocity and ovality. An analysis procedure for subsea jumper systems is proposed and an applied example is suggested. The applied example involves a sensitivity analysis of the three variables of temperature, velocity and ovality. When temperature is predominant, ovality tends to slightly overestimate the collapse strength of the jumper compared with velocity. These results suggest that the temperature of the pipeline fluid plays a significant role when ovality and velocity are predominant.

Scn.	Temp. (°C)	Ovality (%)	Vel. (m/s)	Collapse pressure (MPa)		Scn.	Temp. (°C)	Ovality (%)	Vel. (m/s)	Collapse pressure (MPa)	
				FEA	DNV					FEA	DNV
1	159.56	2.79	4.16	58.60	68.61	26	183.57	0.63	4.48	64.60	74.18
2	198.54	2.49	1.92	54.80	66.86	27	72.51	2.85	3.36	67.95	75.24
3	54.50	0.27	2.88	82.78	87.25	28	138.55	1.17	4.32	60.30	75.62
4	174.56	1.35	4.64	62.55	72.33	29	150.55	2.97	2.48	58.73	68.65
5	66.51	0.69	2.96	78.78	84.08	30	192.57	2.07	1.68	57.83	68.62
6	102.53	1.47	3.92	69.53	77.19	31	132.54	2.13	1.20	63.68	72.67
7	63.51	2.61T	2.08	70.20	77.05	32	81.52	2.55	4.24	67.95	75.44
8	99.53	0.45	4.80	74.73	81.33	33	51.50	2.43	3.68	72.90	78.95
9	186.57	0.99	3.60	62.73	72.66	34	168.56	1.65	3.04	67.95	71.75
10	123.54	2.19	1.76	72.45	73.09	35	126.54	1.83	1.52	65.43	74.12
11	108.53	1.05	4.72	79.88	78.29	36	57.50	0.03	2.40	76.50	87.94
12	156.55	0.57	3.44	76.34	76.43	37	153.55	0.93	1.36	66.60	93.55
13	111.53	1.11	4.40	70.20	77.85	38	144.55	0.39	1.04	69.78	78.03
14	96.52	2.31	2.00	74.93	74.67	39	180.57	1.95	3.20	59.63	69.9
15	75.51	1.77	1.12	81.23	78.86	40	87.52	0.87	3.76	74.70	80.99
16	78.52	0.21	4.56	79.04	84.7	41	141.55	1.23	1.28	66.60	75.18
17	69.51	1.59	3.52	83.25	80.19	42	135.54	0.81	2.24	69.03	77.15
18	165.56	2.91	1.60	64.80	67.84	43	171.56	2.67	2.32	57.83	68.19
19	195.57	1.89	2.56	65.43	68.99	44	60.51	1.53	3.84	75.83	81.46
20	84.52	1.41	1.44	81.63	79.27	45	129.54	1.29	4.88	67.50	75.83
21	105.53	0.15	1.84	84.63	82	46	177.56	2.37	2.64	58.28	68.74
22	117.53	2.01	2.16	73.80	74.15	47	147.55	0.09	3.28	66.94	78.92
23	189.57	0.75	2.72	71.35	73.26	48	93.52	0.33	4.96	75.91	82.43
24	114.53	2.25	4.08	73.13	73.55	49	90.52	0.51	4.00	75.85	82.06
25	120.54	1.71	2.80	74.93	74.98	50	162.56	2.73	3.12	58.50	68.61

Table 4: Analysis results.

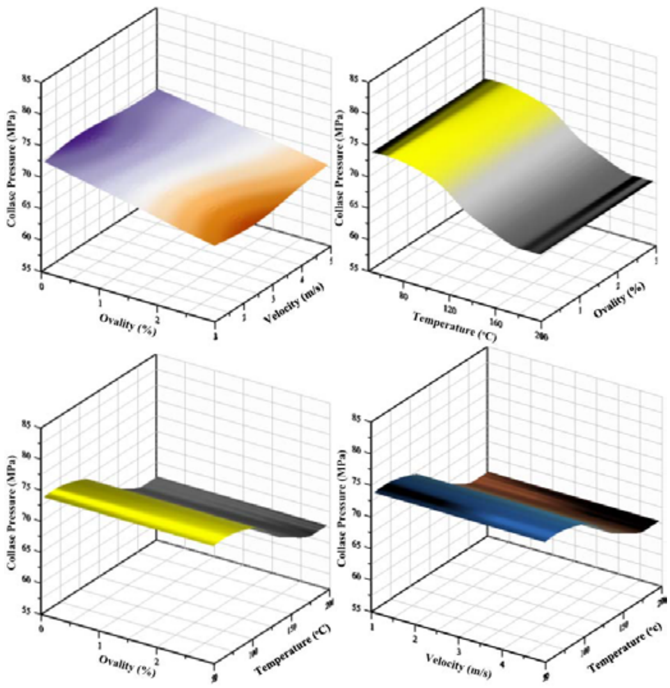


Figure 9: Response surface of the collapse pressure in terms of velocity, temperature and ovality.

Concluding Remarks

This paper presented the results of an investigation of the collapse strength of subsea jumper pipe of varying shapes by considering temperature, ovality and internal fluid velocity. The FSI modelling technique used is this study, which incorporates all of the significant behavioural effects that influence the thermal and geometrical characteristics of a jumper for operating, hydraulic and service fluids, was also described. Detailed numerical analyses were carried out in this FEM-CFD-based parametric study with the aim of determining the sensitivity of design parameters to assist in making recommendations for an optimum jumper system. The results presented here only considered single-phase thermal flow. Thus, much future work is required to identify the effects of design variables in multiphase flow and the coupling effect of different fluids.

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